PRE-LAUNCH RADIOMETRIC PERFORMANCE CHARACTERIZATION OF THE ADVANCED TECHNOLOGY MICROWAVE SOUNDER ON THE JOINT POLAR SATELLITE SYSTEM-1 SATELLITE

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ABSTRACT

The Advanced Technology Microwave Sounder (ATMS) is a space-based, cross-track radiometer for operational atmospheric temperature and humidity sounding, utilizing 22 channels over a frequency range from 23 to 183 GHz. The ATMS for the Joint Polar Satellite System-1 has undergone two rounds of rework in 2014-2015 and 2016, following performance issues discovered during and following thermal vacuum chamber (TVAC) testing at the instrument and observatory level. Final shelf-level testing, including measurement of pass band characteristics and spectral response functions, was completed in December 2016. Final instrument-level TVAC testing and calibration occurred during February 2017. Here we will describe the instrument-level TVAC calibration process, and illustrate with results from the final TVAC calibration effort.

***Index Terms*—Calibration, Advanced Technology Microwave Sounder (ATMS), Joint Polar Satellite System (JPSS), Suomi National Polar-orbiting Partnership (SNPP)**

1. INTRODUCTION

The Advanced Technology Microwave Sounder (ATMS), developed by Northrop Grumman Aerospace Systems (NGAS), and procured by NASA, is the new-generation microwave sounder for the NOAA fleet of operational polar-orbiting meteorological satellites. It replaces, and combines, while providing enhancements to, the capabilities of the Advanced Microwave Sounding Units (AMSU-A and -B), which first entered service in 1998, as well as the Microwave Humidity Sounder (MHS, which itself replaced AMSU-B in 2005).

The first ATMS radiometer was launched aboard the Suomi National Polar-orbiting Partnership (SNPP) satellite in October 2011 [1], [2]. The second ATMS is manifested on the Joint Polar Satellite System-1 satellite (JPSS-1). ATMS provides 22 channels over a frequency range from 23 to 183 GHz for temperature and humidity sounding. Like AMSU-A on the Aqua and MetOp platforms [3], ATMS is also accompanied by a hyperspectral infrared sounding instrument on the same satellite, in this case Cross-Track Infrared Sounder (CrIS). Several schemes for combined atmospheric retrievals from such microwave and hyperspectral IR sensors have evolved over the years [3], [4]. However, under cloudy conditions, ATMS-only retrievals of temperature and humidity profiles retrievals have a distinct advantage, because microwave sensing can penetrate clouds, and thus no cloud clearing algorithm is necessary.

The JPSS-1 ATMS first underwent instrument-level TVAC testing in 2014. Due to performance issues, the TVAC campaign was curtailed. JPSS-1 ATMS was reworked and repaired, and TVAC regression testing was completed in December 2015. Good results were obtained at that time: NEDTs were well within specification; $\Delta G/G$ obtained from noise power spectra indicated that JPSS-1 ATMS would have less scan-to-scan "striping"—considerably less in some channels—than the SNPP ATMS; however, nonlinearity appeared to have increased somewhat for some channels since the 2014 TVAC calibration.

Yet, during observatory-level (on the spacecraft) testing in mid-2016, JPSS-1 ATMS exhibited anomalous behavior. Therefore, ATMS was de-integrated from the JPSS-1 spacecraft, and shipped back to the instrument contractor (NGAS) for rework and repair. Subsequently, V-, W-, and G-band shelf regression testing was completed by the end of 2016. A second and final round of instrument-level TVAC regression testing was completed in February 2017.

2. TVAC CALIBRATION PROCEDURE AND DATA ANALYSIS

Here we present a simplified description of the instrument-level pre-launch TVAC calibration ("TVAC Cal") procedure, and how the data is analyzed by the TVAC calibration software to estimate NEDT and the nonlinearity of the radiometer transfer function for each channel. At the NGAS sensor development facility in Azusa, CA, the ATMS instrument is placed inside a TVAC chamber, with electrical connections to the outside from a cable port. Two calibration targets are positioned at each of the two separate antenna apertures (K/Ka/V band and W/G band): a cold target (simulating the cold space calibration) positioned at the cold calibration sector scan angles, and a scene target placed within the scene sector. The internal hot target of the instrument is used as the hot calibration reference. All three targets are high precision targets with an emissivity greater than 0.9999. The TVAC chamber is pumped down, and three "calibration cycles" are completed. A calibration cycle is defined by the instrument baseplate temperature. Before a cycle, the baseplate temperature is adjusted so the V-band shelf platinum resistance thermometers (PRTs) stabilize at one of three specified temperatures, labeled cold, "mid", and hot, spanning the range of expected temperatures on-orbit, with "mid" representing the nominal on-orbit temperature.

The cold target, which simulates the on-orbit cold space calibration, is held at a constant physical temperature of about 85 K. During each calibration cycle, the scene target physical temperature is cycled through a sufficient number of evenly spaced scene temperature steps between the cold target temperature and 330 K to enable accurate determination of channel nonlinearity, as described later in this section. At each scene temperature step, the scene and cold targets are monitored using many internal PRTs, and the temperatures of the scene targets and the instrument receiver shelves must satisfy stringent stability criteria during the collection of the radiometric calibration data.

The next three paragraphs describe the method for calibrating the scene target measurements for each channel, and how the resulting measured scene brightness temperatures are used to determine channel NEDT and nonlinearity.

For each scene temperature step, the calibration software computes "reference" brightness temperatures (TB) for all target measurements, using the target emissivities and physical temperatures. The raw data counts for the hot and cold target, and the corresponding reference TBs, are averaged for each scan, over the range of scan positions applicable for each target. To obtain a "measured" scene TB for each scene target measurement, the scene target counts are calibrated against the scan-averaged counts and reference TBs for the cold and hot targets, using the standard two-point linear calibration equation. (Prior to this step, the scan-averaged hot and cold target counts and reference TBs are interpolated to the time of the scene measurement, using a least square linear fit on the 8 surrounding scans.)

Finally, for each scene measurement, the scene measurement error is computed by subtracting the scene reference TB from the scene measured TB. The standard deviation of the ensemble of scene measurement errors, over the entire data set from a single scene temperature step, is a good measure of the Noise Equivalent Delta Temperature (NEDT) for that scene temperature step. The average of this ensemble of scene measurement errors is called the accuracy error for the scene temperature step, and is used in estimating a channel nonlinearity parameter, as described next.

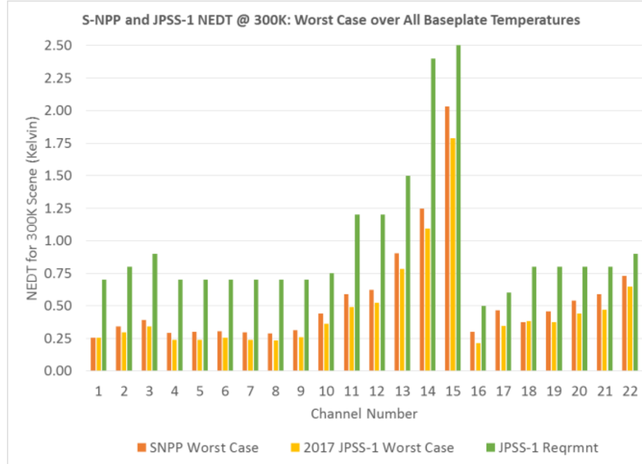

Figure 1: Comparison of worst case NEDT over all redundancy configurations and baseplate temperature cycles, for a scene temperature of 300 K, for SNPP and 2017 JPSS-1 ATMS. The PRD requirement for the 300 K NEDT is shown as the final bar.

The accuracy errors for a given calibration cycle, one for each of the scene temperature steps, are plotted against the corresponding set of step-averaged scene reference TBs, and a parabolic fit is generated. The parabola is extrapolated down to the on-orbit cold space temperature (3K), and a straight line is fit between this point and the point on the parabola at the assumed on-orbit temperature of the hot target. The difference between the straight line and the parabolic fit represents the nonlinearity of the radiometer transfer function. This quadratic nonlinearity curve, which is by definition zero at the cold and hot calibration temperatures, has a maximum halfway between the cold and hot calibration points.

These maximum nonlinearity estimates, one for each of the three V-shelf temperatures, are the only parameters derived from TVAC Cal that are used directly in the ATMS Sensor Data Record (SDR) Algorithm. They are scaled to the actual on-orbit hot target physical temperature, and then interpolated to the actual V-shelf temperature, before use in the SDR algorithm nonlinearity correction.

At the highest scene temperature step (330K) of each calibration cycle, additional data is collected to derive the short-term Noise Power Stability (NPS) and short-term gain fluctuation ("$\Delta G/G$") for each channel. The test procedure consists of collecting 100 sets of the following: a long point-and-stare at the center of the scene target to collect several thousand samples, and a short point-and-stare at the center of the cold target and then the hot target, to collect sufficient

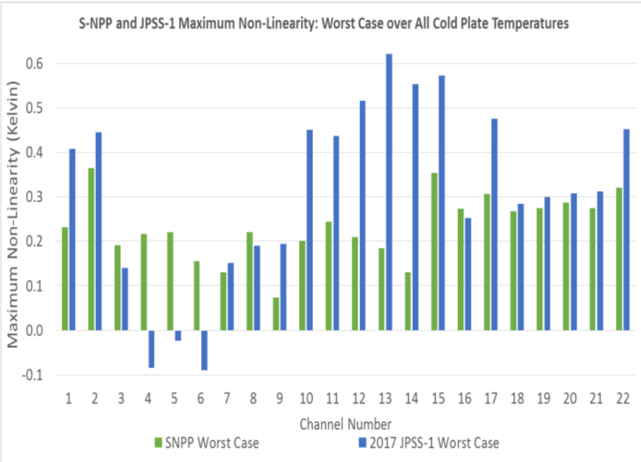

Figure 2: A comparison of maximum nonlinearity for SNPP TVAC Cal and the 2017 JPSS-1 ATMS TVAC Cal. These are worst case over all redundancy configurations and baseplate temperatures.

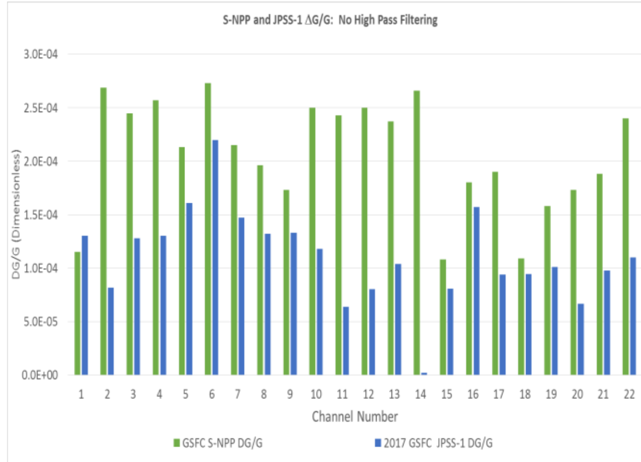

Figure 3: Comparison of ΔG/G for the nominal base-plate temperature cycle of SNPP ATMS and the 2017 JPSS-1 ATMS TVAC Cal.

samples for calibration. The measured and reference TBs for the scene samples are computed in similar fashion to the TVAC Cal processing just described. The differences between the measured and reference scene TBs are computed for each set, and an FFT is performed on each of the 100 sets of differences. The 100 FFTs are then combined to form an averaged noise power spectrum.

From the averaged noise power spectrum, the total equivalent noise temperature, T_{total}, is computed from the entire frequency range in the spectrum. The white noise portion of the noise temperature T_{white}, is computed from the high frequency part of the spectrum (above the 1/f noise break-point). T_{white} is equivalent to the short-term, observation-to-observation or "along-scan" NEDT at 330K. NPS is then computed as the root-difference-square between T_{total} and T_{white}: it is equivalent to what one would root-sum-square with the along-scan NEDT to obtain the long-term or "along-track" NEDT. Thus NPS is a measure of the along-track (scan-to-scan) "striping" which became evident during the SNPP ATMS on-orbit calibration [5]. Further, ΔG/G is computed as the ratio of the NPS to the system temperature; it is the ΔG/G one would use in the standard NEDT equation to obtain the along-track NEDT at any scene temperature.

3. 2015 TVAC CALIBRATION RESULTS

The TVAC Cal procedure and analysis for NEDT and nonlinearity determination is repeated for 4 of the 8 possible redundancy configurations (RCs) of the sensor electronics. The worst case NEDT over the 4 RCs, at 300 K scene temperature, is compared with the requirements value from the JPSS-1 ATMS Performance Requirements Document (PRD) for requirement verification. Figure 1 compares the worst case NEDT at 300K scene temperature for the SNPP TVAC Cal, the February 2017 JPSS-1 TVAC Cal, and the PRD requirements value. Clearly, JPSS-1 ATMS offers slightly better NEDT performance than SNPP ATMS for 20 channels, with nearly identical performance for the other 2.

Figure 2 shows the analogous comparison for maximum nonlinearity, assuming a cold space temperature of 3K and a hot target temperature of 330K. As per the PRD definition and the TVAC Cal Test Procedure, the nonlinearity values have been divided by 2 (AMSU heritage). For JPSS-1, the SNPP requirement on nonlinearity has been replaced with a requirement on nonlinearity knowledge uncertainty, as there is a nonlinearity correction in the JPSS SDR algorithm. One can clearly see that the nonlinearity performance of JPSS-1 is worse than SNPP for the K/Ka band channels (1 and 2), the 200 mb to 1 mb atmospheric temperature sounding channels (9-15), the 165.5 GHz channel (17), and the narrowest 183 GHz channel (22). On the other hand, the nonlinearity performance for the surface to lower atmospheric temperature channels (3-6) is better than SNPP. Thus, the importance of carefully measuring nonlinearity for use in the SDR algorithm correction.

Figure 3 compares, for the mid-temperature calibration cycle, the ΔG/G performance for the SNPP ATMS TVAC Cal and the 2017 JPSS-1 ATMS TVAC Cal. As ΔG/G is a good predictor of scan-to-scan striping at any scene temperature, from Figure 3 we expect JPSS-1 ATMS will show less significant striping on-orbit than SNPP ATMS for most channels, with dramatic improvement in channels 2-4, 10-14, 17, and 20-22.

4. CONCLUSION

We have given a brief history of the different TVAC ground calibration campaigns for the JPSS-1 ATMS, and the periods of rework that occurred between them. The basics of the TVAC calibration test procedure and data analysis were described, as it relates to determining NEDT, radiometric transfer function nonlinearity, and finally ΔG/G, which relates to the magnitude of the scan-to-scan (along-track) striping that has been detected in SNPP on-orbit brightness temperature maps.

As of the final 2017 JPSS-1 ATMS TVAC Cal, the JPSS-1 ATMS, compared to SNPP ATMS, showed: slightly better NEDT performance; worse nonlinearity performance for channels 1, 2, 9-15, 17, and 22 (although the JPSS-1 SDR algorithm corrects for nonlinearity so this is of lesser importance); and ΔG/G performance that would indicate much less along-track striping for all but two channels (which have about the same ΔG/G as SNPP), with dramatic improvement for more than half of the channels.

It should be noted, although not shown here, that all 2017 TVAC Cal results are in family with the 2015 TVAC Cal results, with the 2017 results showing a slight improvement in G-band channel NEDT since the 2016 rework, and a small increase in nonlinearity for about half the channels that follows the same trend seen in the 2014 to 2015 TVAC Cal.

5. REFERENCES

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